Contents

Preface xi

Author biographies xv

Acknowledgements xvii

CHAPTER 1 ▪ Quantum harmonic oscillators 1

1.1 QUANTISING THE HARMONIC OSCILLATOR 2
1.2 FLUCTUATIONS AND DISSIPATION IN A QUANTUM HARMONIC OSCILLATOR 8
1.3 MODELLING OPEN SYSTEM DYNAMICS VIA QUANTUM LANGEVIN EQUATIONS 18
1.4 QUANTUM LANGEVIN EQUATION WITHIN THE ROTATING WAVE APPROXIMATION 28

CHAPTER 2 ▪ Radiation pressure interaction 37

2.1 BASIC RADIATION PRESSURE INTERACTION 37
2.2 EFFECTIVE QUANTISATION 39
2.3 DISPERSIVE OPTOMECHANICS 40
2.4 ELECTRO- AND OPTO-MECHANICAL SYSTEMS 43
2.5 MECHANICAL AND OPTICAL DECOHERENCE RATES 45
2.6 DYNAMICS OF DISPERSIVE OPTOMECHANICAL SYSTEMS 47
2.7 LINEARISATION OF THE OPTOMECHANICAL HAMILTONIAN 51
2.8 DISSIPATIVE OPTOMECHANICS 55

CHAPTER 3 ▪ Linear quantum measurement of mechanical motion 57

3.1 FREE-MASS STANDARD QUANTUM LIMIT 58

3.2 RADIATION PRESSURE SHOT NOISE 60
3.3 MEASUREMENT OF MECHANICAL MOTION 64
3.4 STANDARD QUANTUM LIMIT ON MECHANICAL POSITION MEASUREMENT 76
3.5 STANDARD QUANTUM LIMIT FOR GRAVITATIONAL WAVE INTERFEROMETRY 86
3.6 STANDARD QUANTUM LIMIT FOR FORCE MEASUREMENT 88

CHAPTER 4 ▪ Coherent interaction between light and mechanics 93

4.1 STRONG COUPLING 94
4.2 OPTICAL COOLING OF MECHANICAL MOTION 96
4.3 OPTOMECHANICALLY INDUCED TRANSPARENCY 114
4.4 OPTOMECHANICAL ENTANGLEMENT 122
4.5 MECHANICAL SQUEEZING OF LIGHT 140

CHAPTER 5 ▪ Linear quantum control of mechanical motion 151

5.1 STOCHASTIC MASTER EQUATION INCLUDING DISSIPATION 152
5.2 FEEDBACK COOLING 156
5.3 BACK-ACTION EVADING MEASUREMENT 166
5.4 SURPASSING THE STANDARD QUANTUM LIMIT USING SQUEEZED LIGHT 179

CHAPTER 6 ▪ Single-photon optomechanics 193

6.1 OPTOMECHANICAL PHOTON BLOCKADE 194
6.2 SINGLE-PHOTON STATES 196
6.3 SINGLE-PHOTON PULSE INCIDENT ON A SINGLE-SIDED OPTOMECHANICAL CAVITY 202
6.4 DOUBLE-CAVITY OPTOMECHANICAL SYSTEM 206
6.5 MACROSCOPIC SUPERPOSITION STATES USING SINGLE-PHOTON OPTOMECHANICS 219
6.6 SINGLE-SIDEBAND-PHOTON OPTOMECHANICS 230

CHAPTER 7 ▪ Nonlinear optomechanics 231

7.1 DUFFING NONLINEARITY 231
7.2 QUANTUM DUFFING OSCILLATOR 233

7.3 NONLINEAR DAMPING 240
7.4 SELF-PULSING AND LIMIT CYCLES 241
7.5 NONLINEAR MEASUREMENT OF A MECHANICAL RESONATOR 249

CHAPTER 8 ▪ Hybrid optomechanical systems 255

8.1 ELECTROMECHANICAL SYSTEMS 256
8.2 COUPLING A MECHANICAL RESONATOR AND A TWO-LEVEL SYSTEM 261
8.3 MICROWAVE TO OPTICAL INTERFACE. 270

CHAPTER 9 ▪ Arrays of optomechanical systems 277

9.1 SYNCHRONISATION IN OPTOMECHANICAL ARRAYS 277
9.2 IRREVERSIBLY COUPLED ARRAYS OF OPTOMECHANICAL SYSTEMS 293

CHAPTER 10 ▪ Gravitational quantum physics and optomechanics 299

10.1 WHAT IS GRAVITATIONAL DECOHERENCE? 300
10.2 OPTOMECHANICAL TESTS OF GRAVITATIONAL DECOHERENCE 308
10.3 TESTS OF NONSTANDARD GRAVITATIONAL EFFECTS USING GEOMETRIC PHASE 315

APPENDIX A ▪ Linear detection of optical fields 319

A.1 EFFECT OF INEFFICIENCIES 319
A.2 LINEAR DETECTION OF OPTICAL FIELDS 322
A.3 POWER SPECTRAL DENSITY OBTAINED BY HETERODYNE DETECTION 323
A.4 CHARACTERISING THE OPTOMECHANICAL COOPERATIVITY 324
A.5 CHARACTERISING THE TEMPERATURE OF A MECHANICAL OSCILLATOR 326

References 329

Index 355